NHDOT Research Project 26962P
Reducing Cracks in New Bridge Curbs

Task 1: Review of Current Practices and Evaluation of Existing Concrete Curbs

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Submitted by:

Eric Caron (ec1068@wildcats.unh.edu)

Eshan V. Dave (eshan.dave@unh.edu)

Department of Civil and Environmental Engineering
University of New Hampshire
33 Academic Way, W183 Kingsbury Hall, Durham, NH 03820

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1.1 Introduction

Uncontrolled, early-age cracking has been occurring on many concrete bridge curbs managed by the New Hampshire Department of Transportation (NHDOT). The cracking begins to manifest in the first few days after placement. A review of the construction procedures used by the NHDOT as well as a literature review of previous studies is included in this report. Proposed activities for the study are included at the end of the report and are the recommendations of the researchers.

1.2 Problem Statement

The New Hampshire Department of Transportation has been experiencing early-age cracking in many concrete curbs on bridges. The cracking has been observed as early as the first few days after concrete has been poured and the cracks that form pose a significant durability problem as they provide a gateway for water and deicing salts to enter and cause damage which drastically reduces the service life of the curb. Normally it is anticipated that bridge curbs will be replaced at the same time as the deck but with the advent of premature cracking this will likely require the curb to be replaced much sooner. The rapid degradation of curbs will likely mean increased maintenance, shorter service life, and increased life cycle costs.

Figure 1: Sample of cracking on bridge curb in Hampton, NH.

An example of this early-age cracking are bridge curbs in Hampton, NH (Figure 1) along NH Route 101 that were recently replaced. The newly placed curbs were placed in the winter and kept in a heated “greenhouse” enclosures to keep hydration continuing. Figure 1 was taken less than a month after the concrete for the south curb was placed and already exhibited multiple transverse cracks extending fully along each face. The 28-day compressive strength of the concrete used on this curb was approximately 6000 psi.

In March of 2017, the north facing curb was replaced. After five days of wet curing the formwork was removed (although curing was still continued) and four visible cracks had already formed (Figure 2). Three of the cracks extended the full length through the curb whereas one was confined to the top face. All four cracks occurred within the first third of one side of the bridge.

Figure 2: Cracking in the north curb 5-days after placement.

Two of the cracks formed within one foot of the anchor rods used to secure guardrail posts and the remaining two cracks were located “mid-panel”. The term “panel” is used here to describe the section of curb between two guardrail post locations. The curb is continuous with no joints but referring to sections between posts as panels simplifies the identification of crack locations.

Both the north curb and south curb were revisited 42 and 119 day, respectively, after being placed. The south curb had a total of 74 visible cracks and the north curb had 27 cracks.

Figure 3: Crack extending through patch hole left from construction.

Early cracking is also evident in bridge curbs in Cöös County. The bridge in Pittsburg, NH that crosses over Indian Stream on Route 3 had clearly visible cracks at nearly every guardrail post as well as one mid-panel crack at nearly every panel. This bridge is located on one of the only routes to travel through Pittsburg and is therefore subject to a fairly large amount of heavier vehicles including school buses, plow trucks (Figure 4), and the more frequent logging trucks traveling at speeds around 55 mph. Another common observation is that many of the cracks along the bridge curb traveled through circular “patches” filling the voids from formwork ties during the construction process (Figure 3).

Figure 4: Plow truck crossing the bridge over Indian Stream in Pittsburg, NH.

Two bridges along Route 115A in Jefferson, NH were also investigated. Both bridge curbs had been replaced in the past few years and are located approximately one-tenth of a mile apart. One of the bridges was much shorter in span (less than 30 ft.) than other bridges in the study. This short-span bridge showed no signs of cracking whereas the larger bridge over the Israel River showed signs of cracking. The cracking on the bridge extended fully through the curb at nearly every support similar to other bridges in this study but mid-panel cracks were often lower intensity (smaller crack width), confined to the top of the curb, and some panels had multiple cracks. Although cracking on the Israel River curb seemed less severe, the curb showed signs of scaling and pop-outs in addition to cracks (Figure 5).

Figure 5: Bridge over the Israel River in Jefferson. Signs of fatigue clearly visible on surface.

The early-age cracking witnessed in this study suggests that concrete curbs on NHDOT bridges will be much more susceptible to freeze-thaw and corrosive damage much sooner than concrete curbs without cracking. This will lead to increased maintenance as well as a shorter useful life for the curb. Early deterioration of the curb may also lead to additional deterioration of the bride deck. The increased maintenance and lower curb life will lead to increased costs to the NHDOT.

1.3 Study Objectives

The objective of this study is broken into 4 tasks:

1. Review current NHDOT practices, survey and evaluate existing curbs experiencing early-age cracking, and evaluate mix design and test results
2. Construct curbs with varying mix designs and construction processes
3. Survey of concrete curbs constructed in part 2 at regular intervals to document cracking (approximately 3, 7, 14, 21, and 28 days after pouring)
4. Analyze results and provide recommendations to NHDOT

1.4 Research Approach

In order to methodically and efficiently find the cause(s) of premature curb cracking the study will begin with a literature review to find similar problems experienced by various transportation agencies as well as the probable causes and remedies they concluded. The list of probable causes will then be analyzed and reduced as data collected on NHDOT bridge sites makes certain causes unlikely. The list may also be expanded if there is sufficient anecdotal evidence to warrant further investigation.

After the list of causes has been expanded and reduced, researchers will select methods, mix designs, and practices to change as variables for test curbs. The variables to be tested will be picked based on cost, ease of implementation, and the estimated probability the variable will remedy premature curb cracking.

As the test curbs are constructed they will be visited multiple times within 28 days after being poured. At each visit, photos and notes will be taken regarding site conditions and crack propagation. If any conditions are observed that may have an effect on crack generation those will be included in notes as well. Mix design and QA/QC data will also be collected.

Once the test curbs have been completed and the periodic surveys have been conducted an analysis of the data will take place. Following analysis, recommendations will be made to the NHDOT on methods to reduce curb cracking.

Chapter 2: Review of NHDOT Standard Practices for Bridge Curb Construction

2.1 Introduction

The following information regarding concrete design, testing, and construction is based on *Standard Specifications for Road and Bridge Construction* published by NHDOT in 2016. NHDOT personnel have stated that concrete curbs on bridge decks are often poured in the winter months as warmer seasons are often consumed with asphalt pavement work. Personnel have also stated that the type of concrete used in bridge decks is the same concrete used in bridge curbs. All references in parenthesis come from section 520 of Standard Specifications for Road and Bridge Construction.

2.2 Materials

Concrete classification shall consist of those classes listed in Table 1. Concrete bridge decks are typically specified to be constructed with class AA. When class AA concrete is used on bridge decks, retarding admixtures or ASTM C494 type G high range water reducers will not be used if the air temperature is below 50°F (1.2.1.1 & 1.2.2). The cement used in concrete shall either be type II or type IP (2.1). It should be noted that NHDOT does not have any special considerations for supplementary cementitious materials (SCMs) used in bridge decks compared to other concrete applications.

All mix designs must be submitted for approval by NHDOT's Bureau of Materials and Research prior to being used. The submission must contain data from the mix design including compressive strength, amount of cement, aggregate gradation, air content, water/cement ratio, and chemical admixtures (2.11.2.1). All ingredients used in mix design shall be measured by weight unless given permission otherwise. Mortar proportions in concrete shall be kept as low as possible without losing the desired workability. Mixing water will also be kept to the minimum to produce the required consistency of concrete. The slump required for bridge decks and sidewalks is 2-3 inch (3.1.4.1).

Nominal size for coarse aggregate used in class AA shall be between 3/4 inch and No. 4 in size. Aggregates used in concrete must not be frozen unless they can be dispersed during mixing (2.2). From a batching perspective, all aggregate shall be adjusted from saturated surface dry (SSD) condition to account for absorption of water by aggregates (3.1).

Table 1: NHDOT concrete classification adapted from Standard Specification for Road and Bridge Construction.

Concrete Classes				
Concrete Class	**Expected 28 Day Compressive Strength (psi)**	**Maximum Water/Cement Ratio**	**Entrained Air (%)**	**Permeability Value[2] (kΩ-cm)**
AAA[1]	*5000*	*0.4*	*5 to 9*	*20*
AAA	*5000*	*0.444*	*5 to 9*	*20*
AA[1]	*4000*	*0.4*	*5 to 9*	*20*
AA	*4000*	*0.444*	*5 to 9*	*20*
A	*3000*	*0.464*	*4 to 7*	*10*
B	*3000*	*0.488*	*3 to 6*	
T	*3000*	*0.559*	-----	
F	*30*	*3.0 to 4.0*	*15 to 25*	

1. Deck Overlays.
2. Target values shown are for mix design approval only and are not intended for use as quality control or quality assurance requirements.

2.3 Construction Process

The construction process here outlines procedures from concrete transportation to finishing that relate to bridge deck curbs and cold weather concrete operations. Concrete that is transported to the construction site must be on equipment that has agitating capabilities (3.4.1.3). For QA/QC, concrete that is being placed must be tested for slump, temperature, and air content for the first three loads per pour (3.1.6.2.1.5).

When concrete is to be bonded to existing concrete the existing concrete surface should be abraded and cleaned to provide a proper interlock between the new and existing concrete. Just prior to the placing of fresh concrete, the existing concrete should be wetted to prevent water in the fresh concrete from being absorbed into the existing concrete (3.6.2.2). Once concrete has been placed it shall be properly consolidated through the use of internal vibrators. Upon reaching initial set concrete should not be disturbed by equipment or construction operations for a minimum of 72 hours (3.5.3.1.5). After finishing operations concrete shall not have a load applied to it for a minimum of 12 hours (3.11.2.1). Formwork may be removed after a 24 hour cure time or finishing (3.11.1.1). After initial curing of bridge decks the bridge may be opened up to automobiles. It should also be noted that limits for peak particle velocity for ground vibrations should also be monitored if blasting operations are in the area (3.11.2.3).

Curing of bridge decks, approach slabs, and overlays will follow method “c” curing which includes a 7 day wet cure using burlap, cotton mats, or other approved material. When burlap is used it should be applied to the concrete in a damp condition within 30 minutes after concrete has been finished. Cotton mats should be applied in a dry state within 10 minutes after finishing and immediately wetted (3.10). All shrinkage cracks shall be treated as directed by the engineer (3.12.1.5).

NHDOT outlines procedures for cold weather concrete operations in the standard specifications. When the average temperature drops below 35°F for more than one day then preventative measures should be used in order to keep concrete from freezing (3.7). An enclosed housing should be created with weather tight material around the entire work area and required heating elements (3.7.3.1). When concrete is delivered to the site, for pours less than 24 inches thick, the temperature of the concrete must be between 50°F-70°F. Concrete may be warmed by increasing the water temperature used in mixing up to 160°F and increasing aggregate temperature up to 100°F (3.7.4.1). If concrete cannot be mixed and delivered above 50°F then placement should be cancelled and postponed until conditions improve (3.7.4.2). When concrete is poured make sure all materials that will be in contact with concrete (forms, materials, etc.) should be brought up to 50°F (3.7.4.4). After pouring, concrete temperature shall be maintained at 50°F-100°F for the first 72 hours and between 40°F-100°F for the second 48 hours. The rate of cooling for the concrete should not exceed 1°F/hour (3.7.4.7).

Chapter 3: Literature Review

3.1 Introduction

The following literature review includes a brief introduction on cracking and fatigue in concrete as well as a literature review of previously conducted studies. The studies were gathered from TRID searches focusing on early-age concrete cracking in both bridge decks and bridge parapets. Most of the literature available was concerned with bridge decks. A limited amount of research was reviewed that dealt with restrained concrete shrinkage.

3.2 Literature Review

Fatigue in concrete often manifests itself in the form of cracking, spalling, scaling, pop outs, crazing, or delamination. Frequently fatigue is often the result of prolonged exposure to weather, stresses due to traffic, chemical processes within concrete, improper construction practices, or a combination of the previous items.

Weather has a considerable effect on concrete durability. Since concrete is fairly porous water can pass through the surface and remain inside air voids of the concrete. When temperatures drop in colder climates the water in the voids begins to freeze and place stresses on the concrete matrix. When the stresses become large enough micro-cracks form in concrete. Over the course of many freeze-thaw cycles these small cracks become more prominent and will begin to show on the macro-scale as spalling. In addition to freeze-thaw damage, temperature fluctuations can cause stresses in concrete. For example, concrete used on a bridge deck will expand and contract at a different rate then the steel supporting it. This differential expansion and contraction can put both tensile and compressive stresses on the concrete. Since concrete exhibits relatively low tensile strengths even small tensile loads may lead to cracking.

Traffic, over time, causes concrete to abrade. Abrasion at the surface of cement paste may lead to a condition in which aggregates in the concrete become loose or dislodged. Loading of concrete may also cause concrete to become damaged. For example, traffic loading may cause negative moment areas to develop near bridge. These negative moment areas can create tensile stresses that cause concrete to crack [1].

The permeability of concrete leaves it vulnerable to chemical attacks of various kinds. If concrete is reinforced with steel then water that penetrates into the concrete may begin to cause corrosion at the surface of the steel. As the steel corrodes it may expand up to 6 times the original volume of steel [2]. Another common problem associated with chemical processes is the use of deicing salts on roadways. While deicers do not cause a specific chemical reaction in concrete their presence can cause similar damage to that of freeze-thaw exposure. Deicers can cause salt crystals to grow in concrete creating expansive forces as well as pulling nearby water through capillaries in the concrete creating high osmotic pressures [2]. A common type of chemical reactions that occurs with concrete are alkali-silica reactions (ASR). ASR is the result of reactive silica in the aggregates used in concrete production and the naturally high alkaline environment of concrete. The hydroxides in the alkaline environment react with the silica in the aggregates causing a gel to form. When the ASR gel is introduced to water it begins to swell placing pressures on the concrete which ultimately leads to cracking.

Construction practices that effect durability include improper reinforcement, mix design, placement, and curing. If concrete is inadequately reinforced tensile stresses in concrete may develop and cause cracking. Mix designs have many variables that need to be adjusted and tested prior to the use of the mix. Often durability problems resulting from an improper mix design is caused by a water-cement ratio that is not appropriate. A high water-cement ratio may lead to a more porous concrete which allows more water to penetrate into the structure leading to reduced durability. Placement of concrete may reduce durability if there is poor consolidation of material around reinforcement and formwork, segregation of aggregates and cement paste, incorrect curing practices, or improper finishing techniques that may reduce the amount of air entrained in the concrete. Cracking may also be the result of concrete shrinkage.

A similar issue was faced by the Ohio Department of Transportation. Bridges operated by ODOT were experiencing cracking at intervals over bridges. One finding was that the frequency of parapet cracks increased near bridge piers. Traffic loading created negative moment areas near bridge piers which placed tensile stresses on the concrete parapets leading to cracks. In order to combat uncontrolled cracking researchers recommended using saw cuts in parapets at regular intervals to encourage cracking at those locations. By encouraging cracking at specific locations maintenance crews are more able to manage, monitor and maintain cracks. Saw cuts were recommended to be done while concrete was less than a day old as concrete may begin developing cracks in the first few days after pouring[1].

Similar cracking problems with bridge decks are also frequently researched. Premature cracking in bridge decks can be the result of negative-moment areas, bridge abutments constraining deck, non-uniform concrete curing, and thermal gradients in curing concrete creating tensile stresses in the deck[3]. Research conducted on bridge decks in New York that were experiencing early-age cracking concluded that cracks form in concrete during the period when the cement matrix was weak within the first 48 hours after being cast. The study also concluded that the cracking was the result of shrinkage and thermal stresses[3]. The magnitude of the stresses also depend on the restraint between the bridge deck and bridge structure. Recommendations from this study include keeping air content above 6% (preferably around 8%), having a maximum water-to-cementitious material ratio of 0.42, and a maximum cement content of 317 kg/m^3 (534 lb/yd^3)[3].

Shrinkage compensating concrete has also been evaluated at reducing cracking in bridge decks however shrinkage compensating concrete also comes with increased cost, increased attention during placement, and may not be readily available[4]. A study of bridge deck cracking in Florida found that cracking in bridge decks may be increased by the use of integral abutments as well as using concrete with larger compressive strengths. The study used finite element analysis and identified the causes of cracking to be largely associated with shrinkage, thermal effects, and truck loading[5].

The recommendations made by previously mentioned studies are also echoed by a PennDOT study that recommended limiting cementitious material content to 620 lb/yd^3 and using SCMs, excluding silica fume, to reduce heat of hydration and reduce concrete stiffness. Limiting concrete compressive strength to 4000psi and 5000psi at 7 and 28 days respectively was also advised. The study also encouraged wet curing for 14 days and not letting evaporation exceed 0.10 $lbs/(ft^2 \cdot hr)$[6].

The state of Michigan experienced concrete barriers that were becoming degraded at a much faster rate than other bridge elements. A report from research conducted by MDOT discouraged the use of slip-form concrete barriers. The report also recommended the use of epoxy coated reinforcement to reduce the rate of corrosion of steel in concrete[7].

A report from the National Research Council Canada described the problem of transverse cracking in bridge barrier walls only a few days after concrete placement (in as little as one and a half days in some cases). Many cracks observed in this study had a fairly regular spacing of about 0.8 meters and extended fully through barrier wall. This study used a combination of field data, finite element analysis, and strain gauges to try to determine the causality of cracking. When it came to traffic vibrations the researchers noted that peak strains in the upper portion of the barrier wall were recorded during off peak hours likely due to higher vehicle speeds. One recorded peak in strain resulted in a compressive strain of 44με followed by a tensile strain of 17με. The study concluded that the main result of cracking in barrier walls was due to thermal gradients in the wall resulting in tensile stresses to develop. To remedy this researchers recommended keeping formwork on longer then one day as well as reducing the cement content in concrete. Along with a reduction in cement content a higher water-cement ratio was encouraged to decrease the effects of autogenous cracking which was also considered as a significant contributor to the problem. The cement content used in the study was 450 kg/m^3 (758 pcy) and the water-cement ratio was 0.36. The study also stated that vibrations induced by traffic may have also led to crack formation particularly in the early stages of curing[8].

An article published in 2007 on the subject of reducing cracking in bridge decks stated that no single method of crack reduction is likely to work on its own but must be used in conjunction with multiple reduction methods. Some of the methods mentioned in the article include keeping the water-to-cementitious material content between 0.40 and 0.45 and trying to reduce the amount of cement content per cubic yard. The mix should also include SCMs in order to reduce the heat of hydration. Other modifications to the type of concrete used include specifying the lowest compressive strength that is acceptable for the project as well as using a minimum of a 7 day wet cure. Another suggestion by the article included using shrinkage compensating concrete[9].

A University of Kansas study funded by multiple DOTs to explore how to reduce cracking in bridge decks was published in 2017. The study used Low-Cracking High-Preformance Concrete developed by KDOT and tested it on various bridge decks with a control. LC-HPC uses cementitious material content between 500 lbs and 563 lbs per cubic yard of concrete and a water-cementitious material ratio of 0.42-0.45.The mixture also had air contents between 6% and 9.5% The study concluded that the LC-HPC was superior in reducing cracking in most cases compared to the control decks[10]. The study also concluded that using lower cementitious material, restricting maximum compressive strength, minimizing finishing operations, controlling temperature in concrete, and placing limits on maximum slump can reduce cracking in bridge decks.

3.3 Summary of Literature Review

While many different theories and conclusions were made about the mechanisms of early-age concrete cracking in the literature review some general mechanisms appear to be working in many of them.

Traffic loading can cause a bridge to flex at constraints or piers creating negative moment areas which place concrete in tension. When the tensile stresses are large enough the concrete will crack. This cracking can also be caused by traffic traveling over the bridge creating vibrations that propagate through the bridge structure and can cause rapid strains which may lead to cracking.

Thermal stresses caused by expansion and contraction as well as thermal gradients created during placement can create tensile stresses in concrete which lead to cracking. Thermal issues may also develop due to non-uniform curing as heat is generated during the hydration process. In addition to thermal gradients as concrete hydrates and dries the concrete may begin to shrink which also induces tensile forces in concrete leading to cracks.

Some recommendations posed by the studies include limiting cement content (preferably below 534 pcy), using SCMs (except silica fume), limiting compressive strength to the lowest acceptable value, using a w/cm between 0.40 and 0.45, performing saw-cuts to promote cracking in specific areas, and using an air content greater than 6%. These modifications aim at increasing flexibility in concrete as well as reducing the amount of shrinkage experienced by the concrete elements.

Chapter 4: Proposed Curb Construction and Material Specifications Trials for Evaluation

Based on field observations and literature review of previous studies the researchers of this study suggest some potential remedial processes and measures to be tested that may be likely to reduce early-age curb cracking on future bridges.

1. Vibration Reduction- Reducing vibrations on the bridge deck caused by traffic prior to the concrete curb reaching significant load capacity may reduce stresses and strains in the curb caused by the deck acting compositely with the curb. This early composite action may strain the curb, particularly at the top face, and cause small cracks that grow when subject to repeated vibrations. This vibration may be reduced by:
    a. Decoupling the curb from the deck- This method reduces the amount the curb and deck act compositely reducing curb strains. Decoupling may be difficult as guardrails must be unaffected in their ability to restrain vehicles.
    b. Preventing traffic- Preventing traffic from crossing the bridge removes vibrations experienced by the bridge and therefore any stresses and strains experienced by the curb acting compositely. While this may be difficult to do for a curb pour alone it may be possible to achieve the same effect by pouring decks and curbs at the same time.
    c. Reducing traffic speeds- Reducing the traffic speed over the bridge may be an alternative to closing the bridge down. Reducing traffic speeds will decrease the amount of stress that propagates through the bridge as suggested in the Canadian study.

2. Precast Curbs- Using precast concrete and placing curbs at a later date removes the curb from an environment where it would have to harden under vibration stresses as well as thermally induced stresses. Using precast concrete will also allow for controlled curing.

3. Reduce Concrete Stiffness- A stiff concrete does not allow the curb to flex appropriately and creates locations of high stress and strain in an element. If the curb cannot be ductile enough to transfer load effectively it will result in cracking. This may be accomplished by increasing air entrainment, limiting the maximum compressive strength of the concrete, or using SCMs. Using concrete with an air content near 9% as well as having a compressive strength near 3500 psi may provide sufficient flexibility.

4. Fiber Reinforcement- Fiber reinforcement may be able to reduce the propensity for a crack to expand by transferring tensile loads through the fibers.

5. Modifications to the Guardrail Post Assemblies- Since many cracks appear to be forming at or near guardrail posts one solution may be to look at how guardrail posts are affixed to the curb as well as the reinforcement located around the post.

6. Reducing thermal effects in concrete- Reducing the amount of cement content in a mix results in lower heat of hydration and therefore smaller thermal gradients to develop. Using SCMs can also reduce the heat of hydration developed in curing. Also maintaining as small of a temperature difference as possible between the existing bridge deck, rebar, and concrete to be placed may reduce tensile cracks caused by thermal expansion and shrinkage.

7. Alter casting season- Since concrete is difficult to place properly in winter conditions placing a curb during spring or summer months may eliminate any cracking resulting from improper cold weather concreting procedures.

8. Modifications to curing procedure- Challenges with curing in the winter include the use of enclosures during the curing process. These enclosures are intended to keep warm conditions during the curing process so the wet burlap and concrete do not freeze. One concern is that the added heat in combination with low relative humidity increases the rate of evaporation and does not leave a sufficient amount of moisture for the concrete to properly cure. By applying more moisture and a longer wet cure some of the durability issues that would normally arise may be mitigated.

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